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The Geological Significance of Gas Chimneys and their Relevance to Petroleum Exploration

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Abstract

A gas chimney is the seismic expression of gas escaping from the deeper part of a petroliferous basin. The existence of gas leads to a sudden reduction in the intensity of seismic reflections or may result in their complete absence within the area. Gas chimneys are observed mostly in low-permeable cap rock shales. Explorers are interested in identifying their spatial link and connections to traps containing hydrocarbons and hydrocarbon sources. The morphology of chimneys immediately beneath the reservoir provides information about the vertical hydrocarbon charging into the reservoir. Gas chimneys are often associated with faults. The existence of gas chimneys along fault lines suggests that these faults are either currently open or have been open for a significant duration, allowing for the migration of fluids through them. The morphology of the chimneys immediately overlying the reservoir offers information about the top seal. Examples from Borneo illustrate cases where gas chimneys were either drilled through or avoided as a geohazard mitigation measure. Gas chimney interpretation is increasingly significant in petroleum exploration and continues to evolve as a valuable tool.

Keywords: *Gas Chimney, Geohazards, Hydrocarbons, Morphology, Pockmarks, Reservoir, Seafloor*

1.0 Introduction

Gas chimney is an interpretative term for the seismic expression of gas escaping from the deeper part of the basin. Gas chimneys are described as clouds, bags, or plumes based on their seismic morphology. Gas chimneys appear as low-quality seismic responses with mostly vertical bodies of varying dimensions. Seismic data associated with gas chimneys manifest as wipeouts, characterized by a lack of continuity in reflectors and diminished reflection amplitudes compared to adjacent regions (Figure 1). The presence of gas leads to a sudden reduction in seismic reflections, which may either significantly weaken or completely vanish within the affected area. Gas chimneys are observed mostly in low-permeable cap rock shales. Chimneys often extend across multiple stratigraphic intervals without apparently deforming the host rock. Deformation may still occur on a sub-seismic scale. However, micro-fractures must exist in the low-permeable cap rocks or diffusion of ascending gas could result in gas chimneys in such rocks. Gas chimneys typically form predominantly along fault planes, where gas migrates from deeper stratigraphy into the overburden, which is primarily composed of shale with restricted permeability[1]. Vertical migration is a fractal process and not a specific process that changes from level to level. Gas chimneys are often seen in offshore petroleum-rich basins; however, there is limited understanding of their presence on land, where seismic columnar anomalies are typically ascribed to inadequate data quality or processing artifacts. In the past, the cross-sectional shape of the leakage pattern was designated as the 'chimney effect'. A specific manifestation of this chimney effect at the surface is described as a halo pattern situated directly above the reservoir[2].

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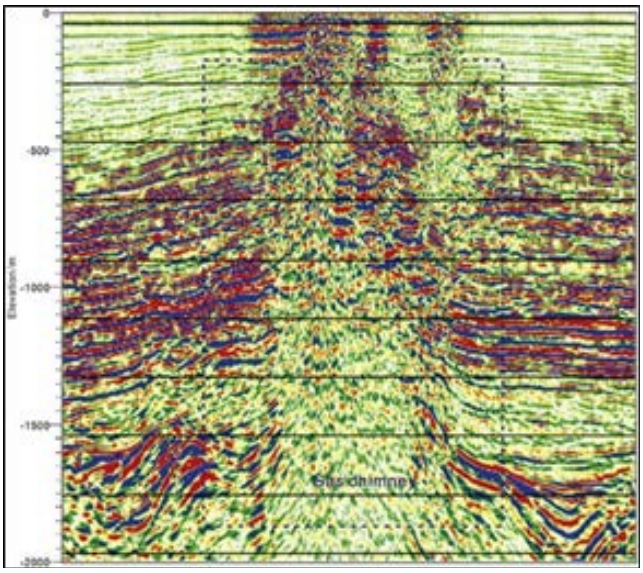


Figure 1. Example of a gas chimney with weak reflection amplitudes[3].

The precise configuration of a gas chimney is challenging to identify on standard seismic displays. Typically, only larger chimneys are readily discernible. From a geological perspective, these structures can be regarded as valves that facilitate the release of gases through faults and permeable sediments[4]. Seismic noise generated by them has frequently been regarded as a factor that degrades the quality of seismic reflection events. But in recent times, they have been enhanced into significant exploration tools by way of advanced seismic technology. Gas chimneys are identified by their characteristic vertical structure and low-frequency chaotic fluctuations in seismic data, which obscure the seismic images. These disturbances are interpreted as resulting from the movement of fluids or free gas. The upward-moving gas cuts across stratigraphy and leaves a trail that we call a gas chimney.

2.0 Significance in Exploration

The occurrence of gas chimneys is a prevalent leakage phenomenon found above gas fields. The relevance of these formations in the context of gas and oil fields, along with the volume of leakage from the reservoirs they signify, continues to be a matter of debate. Nonetheless, they generally provide substantial evidence of either past or ongoing gas presence in the underlying reservoirs. Furthermore, gas leakage in an oil field can alter the Pressure, Volume, and Temperature (PVT) conditions at the reservoir level, affecting the overall charge of the reservoir.

Numerous hydrocarbon-producing basins globally are primarily influenced by vertical hydrocarbon migration. Gaining insights into the migration pathways, the structural stability of the traps, and the locations of hydrocarbon generation significantly mitigates exploration risks. Studies of petroleum systems elucidate the genetic connections between a body of active source rock and the resultant accumulations of oil and gas[5]. The key elements located in time and space include source rock, reservoir rock, seal rock, and overburden rock. The processes that take place involve the formation of traps, along with the generation, migration, and accumulation of oil and gas. A comprehensive understanding of the petroleum system is essential for successful exploration[6]. Gas chimneys are features linked to the movement of hydrocarbons or free gas, resulting in vertical irregularities within seismic data. Their presence above reservoirs serves as a significant indicator of an active petroleum system, and mapping these structures is beneficial for minimizing exploration risks, thereby enhancing the likelihood of successful outcomes. Gas chimneys are the most prominent vertical hydrocarbon migration indicators.

3.0 Characteristics of Gas Chimneys

Gas chimneys have often been noted in connection with the production of oil and gas fields[7]. Gas chimneys are often referenced but rarely thoroughly elucidated. Explorers are keen to establish the spatial relationships and connections between gas chimneys and traps that may harbour hydrocarbons and their sources. The migration of hydrocarbons is observed in seismic records as areas characterized by vertically aligned, chaotic, low-energy data. However, at greater depths, these "chimneys" can span over large areas and are often associated with oil migration. The diffuse characteristics of these chimneys complicate their mapping within seismic data. Imaging beneath gas-obscured regions has historically posed significant challenges. Consequently, specialized chimney analysis tools using multiple attributes enhance seismic imaging capabilities. The technique of chimney detection serves as an exploration tool that yields critical insights for evaluating prospects and finding both charged and

non-charged prospects. This method employs multi-trace seismic attributes, neural network modelling, and the expertise of the interpreter. It is essential to differentiate the seismic representation and interpretation of gas chimneys from seismic artifacts, such as false shallow signatures, which encompass acoustic blanking, bright spot multiples, chaotic reflections, and fault shadows, to accurately assess the presence and maximum depth of gas chimneys. Additionally, it is important to recognize pitfalls such as velocity push-down and pull-up associated with rock properties and multiples.

Seabed characteristics, including pockmarks and carbonate formations, serve as indicators of fluid escape phenomena that could suggest the presence of deeper hydrocarbon deposits[8]. Buried features may be evidence of palaeo-hydrocarbon seepage. The morphology of the gas chimney must be delineated, including the roots or downward termination of the upper section of the chimney, and its lateral extent.

4.0 Gas Chimneys as an Exploration Tool

Gas chimneys are often linked to faults. The occurrence of gas chimneys in conjunction with faults suggests that these faults are either currently open or have been open for a significant duration, allowing fluids to traverse through them. The objective is to determine whether gas chimneys can serve as indicators of leaky faults and aid in the analysis of seal integrity, which is essential for the movement of hydrocarbons through shale, open faults, or fracture systems. This phenomenon can solely take place within an extensional regime due to overpressure within a reservoir, during which the fault or fracture will remain open for a period until the pressure decreases[9]. The shallow gas clouds in the overburden region were formed due to the gas leak from the deeper reservoir, migrating upward through the fault and fracture system.

To assess sealing and non-sealing faults, the identification of gas chimneys along these faults may suggest which faults serve as potential pathways for hydrocarbon migration. Certain chimneys are not only aligned with faults but also with features indicative of gas seepage, such as pockmarks, carbonate formations, and mud volcanoes, as well as shallow and deeper hydrocarbon accumulations. Consequently, these features have highlighted possible hydrocarbon migration routes (Figure 2). The presence of these chimneys signifies fluid movement between hydrocarbon source rocks and reservoirs, between different reservoirs (remigration), and from reservoirs to the seabed.

The morphology of chimneys found directly beneath the reservoir offers insights into the vertical hydrocarbon influx into the reservoir, while those situated directly above the reservoir inform us about the integrity of the top seal[10].

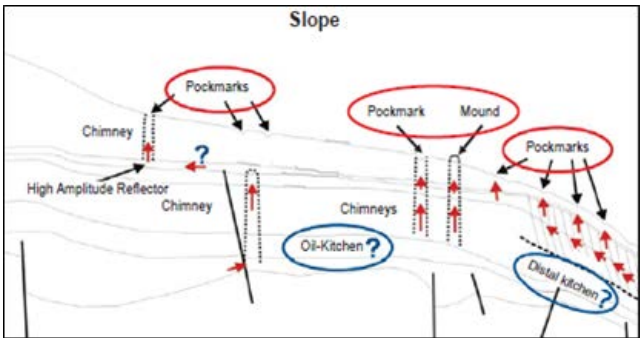


Figure 2. Schematic diagram of the plumbing system in the Colorado Basin illustrating the possible migration pathways at the slope of the basin[11].

The key questions for the explorer would be inter alia.

1. Are the chimneys in the dataset linked to the prospect?
2. Are they associated with faults?
3. If faults are absent, then the morphology of the gas chimney merits attention.
4. When and where does vertical migration dominate, their timing and context?
5. Do we understand the leakage mechanisms?
6. Is the seismic evidence of leakage over a prospect good or bad?

The seismic response resulting from the replacement of pore fluid with gas, and to a lesser extent oil, is evident even at low saturation levels. This raises the question: Do the seismic amplitude anomalies observed in the top seal indicate leakage or suggest a compromised trap? It is important to note that the existence of gas chimneys does not necessarily imply a complete failure of the seal, as numerous traps exhibit both gas chimneys and hydrocarbon accumulations. Several commercial oil fields, such as the Ekofisk and Valhall fields in the North Sea, display these leakage indicators within the overburden. Therefore, the mere presence of a leakage indicator is insufficient to diminish the potential of a

prospect unless supported by additional compelling evidence. Consequently, explorers should focus on elucidating the timing, extent, and mechanisms of any leakage that may have occurred. Top seals may demonstrate transient behaviours that evolve through processes of burial and diagenesis, like reservoirs. Successful commercial accumulations typically result from fewer leaks compared to the influx of hydrocarbons into the reservoir. Borneo serves as a classic example, highlighting gas chimneys situated above oilfields. In one particular field characterized by a dome structure, a significant gas chimney obscures seismic data on one flank, alongside the presence of gas hydrates beneath the bottom simulating reflector. This seismically obscured area, which is substantial, remains undrilled due to the assumption of clay-rich rocks, as drilling through gas hydrates could trigger their dissociation and create geohazards. A key case to consider is the Valhall field in the North Sea, where the undrilled flank beneath the chimney may be part of the same structure as the producing flank, potentially challenging the assumption of clay-rich rock.

Gas chimney identification in conjunction with other structural and reservoir property information aids validation of fundamental geological interpretations such as the origination points of hydrocarbons, spill points, reservoir accumulation, and gas seepage to the surface. The thrust in the exploration workflow is to build the petroleum systems rationale and address in a logical manner elements of a petroleum system and gas chimney analysis does exactly that.

5.0 Implications for Geohazards

A predrill understanding of pore pressure is important for successful drilling. Gas chimneys are usually caused by significant pressure gradients in the sub-surface and are characterized by low velocity and higher pressure. However, pre-drill, the lower seismic interval velocity due to the presence of gas, presents a serious challenge. Pore pressure can be measured directly or estimated using various parameters, recorded during drilling or logging as proxies. This is impractical in most cases, since the gas chimney may be drilled riserless and unless sand stringers occur pressure data acquisition may not be possible. There is no clear relationship between present-day pore pressure and the existence of gas chimneys. The gas chimney being mostly shale, makes it impossible for actual pressure measurements. However, mud gas logging while drilling helps estimate the pore pressure but most riserless sections are not mud logged. Gas chimneys and pockmarks are sometimes associated with near-lithostatic pressures. They are important, as they would show the expulsion from a high-pressure (near-lithostatic) deep-seated gas reservoir and venting up to the surface. Wells drilled on gas chimneys are expected to show high mud gas readings, higher pore pressures, higher temperatures, and lower seismic and sonic velocities.

Gas hydrates are often associated with gas chimneys. Most vertical seismic wipe-outs terminate within the hydrate stability zone, though some extend to seafloor pockmarks, indicating potential gas venting (Figure 3). Within the gas hydrate stability zone, variations in temperature and pressure can lead to the disassociation of the hydrate, facilitating the upward migration of methane to the seafloor and creating a chimney. During warming, expansion of pore volume would result in the formation of cracks whereas contraction of pore volume may result in the closure of cracks[12]. If pore pressures exceed the overburden, the effects of seafloor fracturing may become evident in the vicinity. Certain chimneys are notably affected by the underlying stratigraphy, facilitating the unhindered migration of gas through the sedimentary column. This phenomenon can result in the creation of pockmark-like depressions on the seafloor, where gas is released, or the formation of mounds on the seafloor (Figure 4). Pockmarks release methane, which is subsequently oxidized by bacteria, thereby serving as the foundation of the food chain for vent chemosynthetic communities. Furthermore, various other indicators of gas escape, such as seismic wipe-out zones, can be observed, potentially obscuring areas of shallow gas sand and shallow water flow. An example of a recent and active shallow gas chimney with gas migrating from the crest of the structure also from Borneo is shown in Figure 5.

6.0 Field Examples

Two prospects beneath gas chimneys were identified and the moot question was, Is the chimney due to shear failure related to gas migration along the fault zone? The morphology of the gas bag suggests that this could be a gas cloud trap (Figure 6).

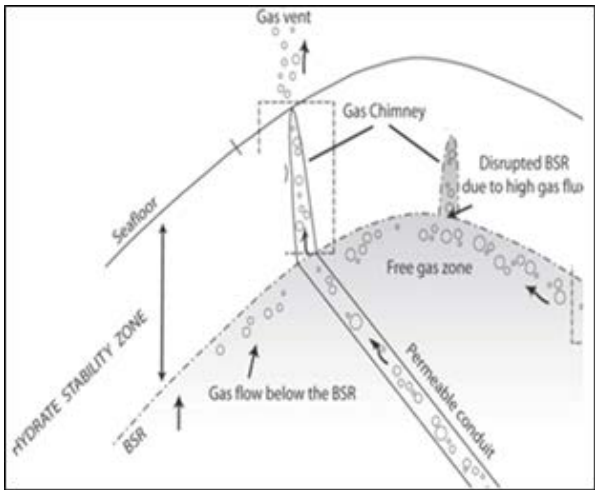


Figure 3. Cartoon of gas chimney associated with gas hydrates (modified picture from[13].

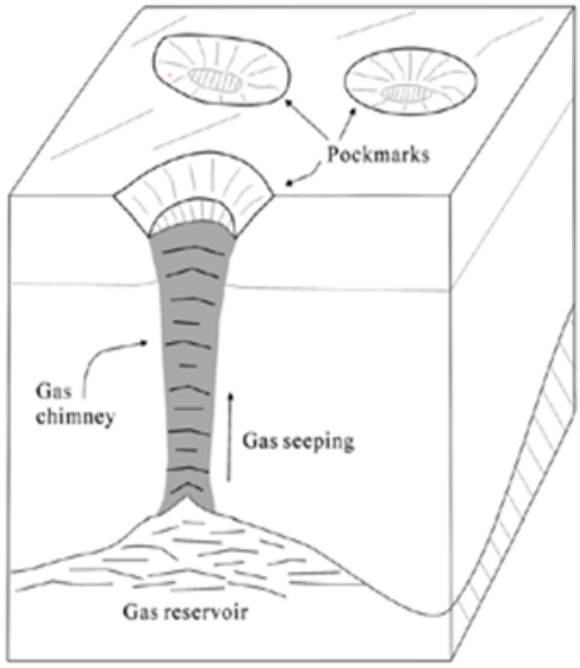


Figure 4. Gas chimney and pockmarks could be evidence of near-lithostatic pressures (modified picture from[14] adapted from[15].

The absence of a gas chimney over the crest of the structure could reveal effective seals. This prospect lies outside the crestal collapse zone of the prospect in Figure 7, but immediately adjacent to the gas chimney. It could be an effective seal as this prospect appears to have low to moderate relief, and the potential reservoir intervals with the highest relief are often on an adjacent structure thus potentially releasing pressure on the reservoir and

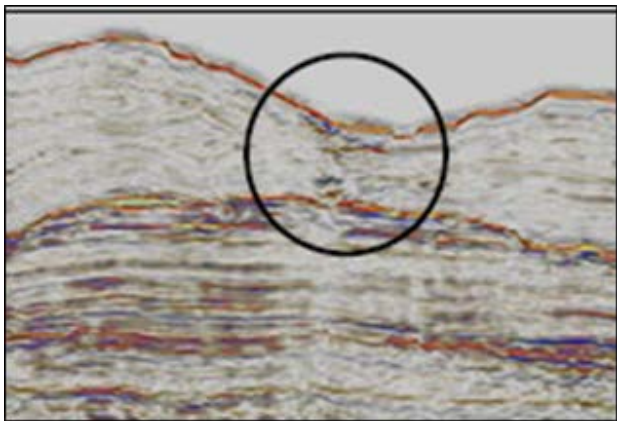


Figure 5. Example of a gas chimney leaking and pockmark (encircled) formed, from Borneo.

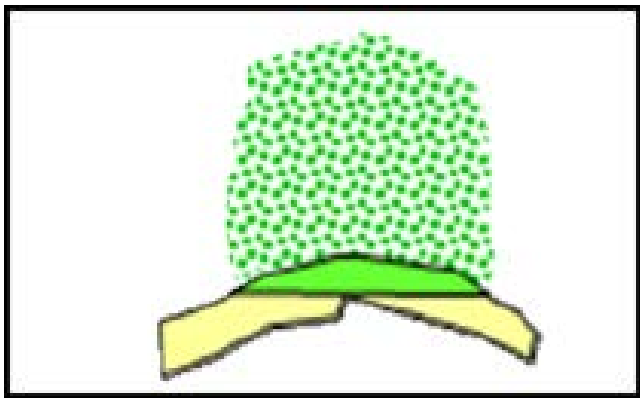


Figure 6. Gas cloud trap.

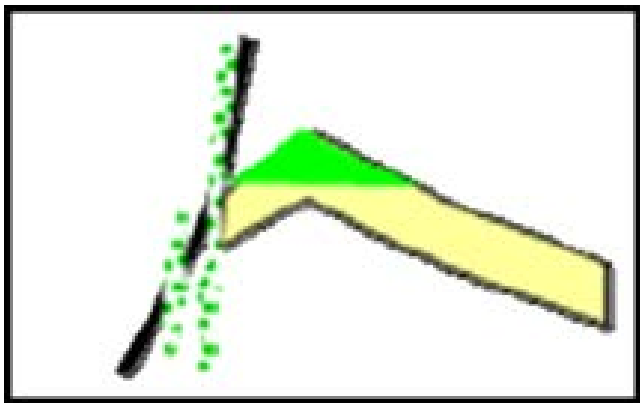
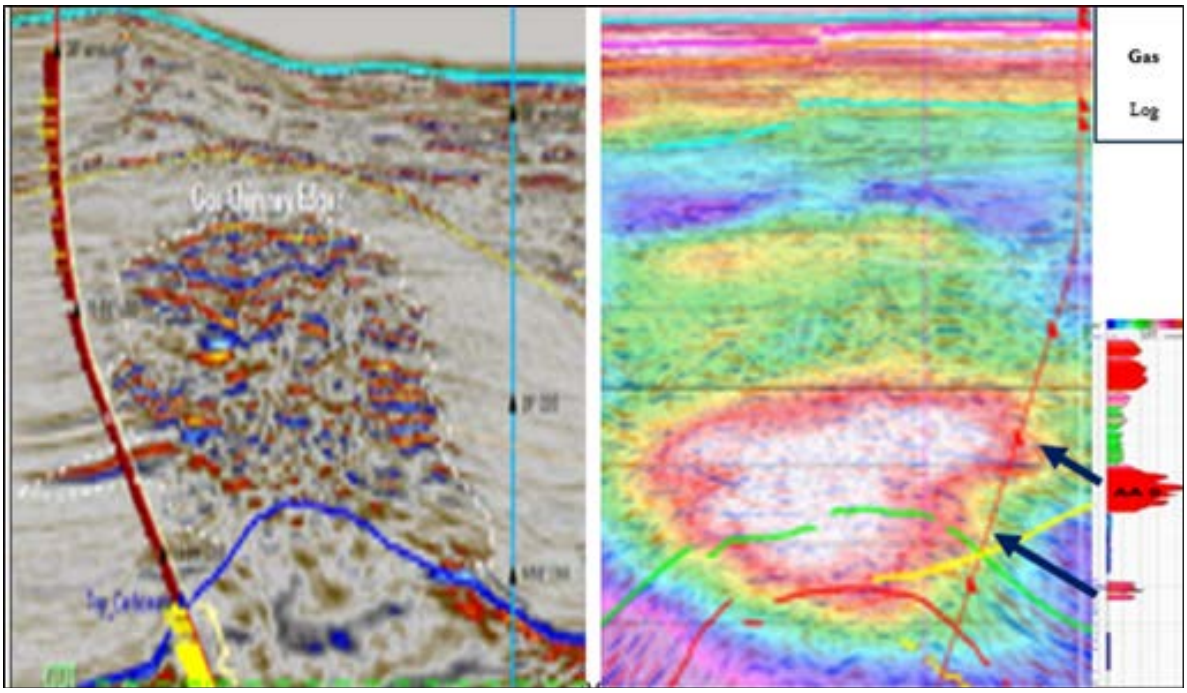


Figure 7. Absence of gas cloud on the crest but adjacent to the gas cloud.

increasing its retention capacity. Hence, it may be of high trap integrity.

Amplitude anomalies linked to gas chimneys are likely to be gas-filled and have to be avoided in drilling. Drilling the wellbore away from the gas chimney by inclining the



a b

Figure 8. **(a)** Inclined well avoids the gas chimney **(b)** Tail end of the gas chimney drilled by the inclined well and indicated increased gas over the background.

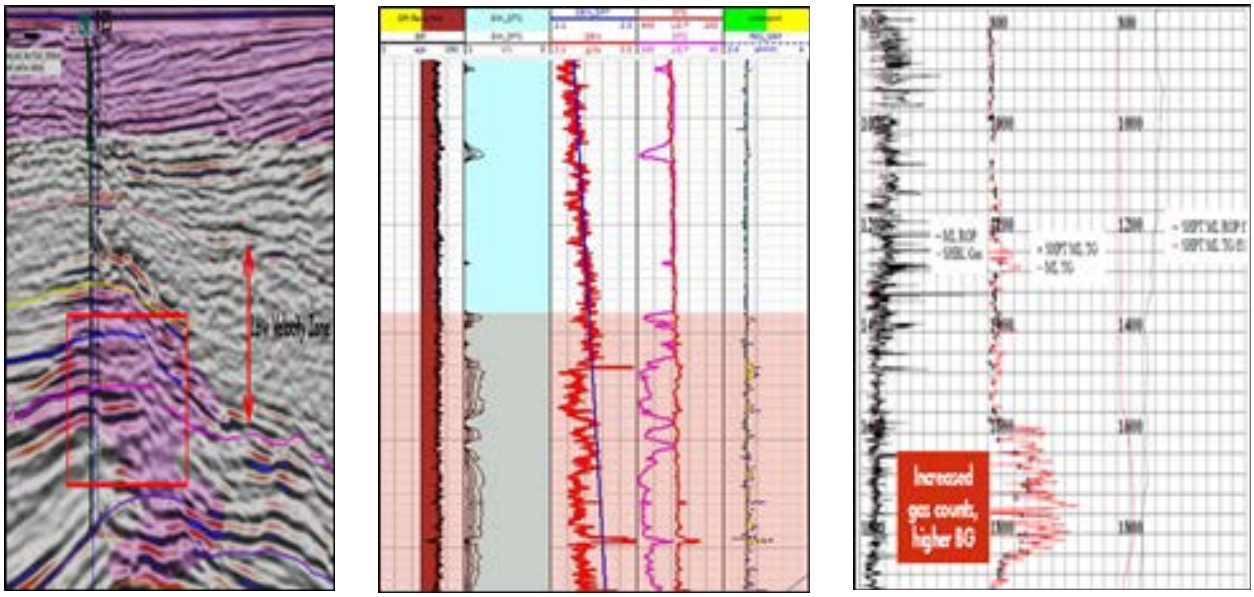


Figure 9. Example of drilling over a gas chimney in Borneo.

well to deeper targets- in consensus with geomechanical understanding is probably the best optimization for safe drilling. As such operators are reluctant to drill through gas chimneys and view it as potential containment candidate. The gas clouds in the illustration from Borneo offshore were avoided by pitching in a directional well to the deeper prospect (Figure 8a and 8b).

The existence of gas within chimneys has been validated by well data, which indicates that wells drilled through gas chimneys exhibit elevated mud gas readings,

as well as reduced sonic velocities and increased pore pressure in the cap rock (Figure 9). This is exemplified by a well drilled above a gas chimney in Borneo.

Offshore data indicated that even low gas saturation is sufficient to create a gas chimney. The gas chimney was perceived both from mud logging and well log data. The observed chimney effect was inversely modeled with inputs from well logs and fluid substituted. Several scenarios were modeled. At low gas saturation itself, the low-velocity gas patches in the low permeable shales were matched.

7.0 Conclusions

Gas chimneys are predominantly observed in shales with low permeability in cap rock formations, indicating the presence of gas leakage from its source. There is significant interest among explorers in determining the spatial relationships and connections to traps that may serve as reservoirs for hydrocarbons, as well as their links to hydrocarbon sources. The presence of gas chimneys along fault lines suggests that these faults are either currently open or have been open for an extended period, facilitating the migration of fluids through them. Understanding gas chimneys before drilling can help in de-risking the prospect and provide insights into potential geohazards. They play a crucial role in revealing the origins of hydrocarbons, their migration routes into a prospect, and the points of leakage, which can result in shallow gas formations and pockmarks on the sea floor. Thus, the interpretation of gas chimneys is a vital asset in minimizing risks associated with exploration projects.

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